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PRIMARY COMPONENTS OF SIMULATED AIR BAG NOISE AND THEIR RELATIVE EFFECTS ON HUMAN HEARING

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13. ABSTRACT

The relative contributions to auditory temporary threshold shift (TTS) of the air bag vehicle volume displacement and of the high frequency noise burst associated with activation, air turbulence, unfolding, etc., of the system were investigated. Ten male university subjects with normal hearing were exposed to each of three conditions: (a) to a positive pressure pulse of 165 dB peak pressure with a rise time of 65 ms and a duration of 960 msec, (b) to a high frequency noise burst in the 350 Hz-2 kHz band at 153 dB rms with rise and fall times of 25 ms and a duration of 400 ms and (c) to a and b presented simultaneously. TTS was measured for 12 discrete frequencies ranging from 125 Hz to 12 kHz for each exposure condition. The high frequency noise burst produced the greatest amount of TTS. The positive pressure pulse produced no measurable changes in hearing levels. The two components occurring simultaneously resulted in less TTS than that produced by the noise burst alone. These results suggest that TTS associated with air bag inflation noise is primarily the product of the high frequency noise. The positive pressure pulse component appears to reduce the effectiveness of the high frequency noise burst in producing TTS. Some implications of this observation relative to the use of air bag restraint systems are discussed.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Air Bag						
Transient Noise						
Impulsive Noise						
Noise						
Hearing						

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PREFACE

INTRODUCTION

National interest in the health and well-being of the average citizen has been extended to the area of automotive transportation and safety, specifically to the personal hazards associated with motor vehicle collision and impact. Each year, over 50,000 persons receive injuries that are fatal, and much larger numbers experience less acute injuries due to motor vehicle impact and collision. Current safety devices, the lap belt and shoulder harness, which are standard equipment in all new passenger vehicles, have demonstrated their efficiency in significantly reducing serious and fatal injuries in collision. However, various statistics reveal that only about four percent of the drivers and occupants in automobiles actually use the total personal protective accessories available. Public education and information programs on the advantages of lap belts and shoulder harnesses have not significantly increased their use by vehicle occupants. A recent approach to this safety problem has focused on the action required of an occupant to engage the safety device, i.e., the positive action required to connect the lap belt and/or shoulder harness into proper position to provide restraint. A possible solution to the non-use problem has emerged in the form of a "passive" safety or restraint system concept that would require no action at all by the motor vehicle occupants but would provide protection in the event of a crash. Of the various concepts of passive restraint systems, which have appeared, such as energy absorbing seats, thickly padded-contoured interior, automatic positioning of belts and harnesses, the inflatable cushion or air bag concept has received the most attention and perhaps is one of the most promising of the various approaches.

The inflatable cushion or air bag system is intended to rapidly inflate in front of occupants upon vehicle impact to cushion the forward motion of the body and provide protection against serious injury. Under normal conditions the inflatable cushion remains collapsed. Upon impact of sufficient intensity, a triggering device activates the inflation system deploying the cushion. Current generation inflation systems capable of satisfying the extremely rapid inflation times (30-70 ms), produce an intense acoustic signal associated with activation of the system. This sudden, high intensity impulse is of concern with regard to possible adverse effects on the human auditory system of individuals inside the vehicle. This concern has been expressed for possible permanent adverse effects on the eardrum membrane and on hearing, as well as possible temporary loss of sensitivity immediately after inflation. The nature of the impulsive noise necessitates investigative work to evaluate such questions, since direct extrapolations from available air bag exposure data to proposed impulsive noise hearing damage risk criteria may not be directly appropriate.

Early in the development of inflatable protection systems, the potential problem of the intense noise was recognized. At those times the primary physical components of the acoustic signal occurring inside an automobile were quantified. Two major characteristics appear in the signal. One component consists of the high frequency energy resulting from activation of the inflation system (usually explosive detonation), air turbulence, rapid unfolding of the cushion and the like. The other component is the low frequency energy (positive pressure pulse) generated by the volume displacement of the rapidly expanding cushion inside the vehicle.

Initial estimates of the potential hazard to hearing of these impulses were obtained from

subjective judgements and experiences of personnel working on the air bag concept development and subsequently, from interpretation of proposed damage risk criteria for impulsive noise. The first experimental investigation of the impulse noise effects on humans exposed 91 subjects to a prototype air bag inflation noise inside a closed automobile (Nixon, 1969). After these findings were reported to the scientific community procedures for assessing the air bag impulse noise and/or evaluating hearing damage risk for exposure to the unique air bag noise were produced by Allen et al (1971) and by Mertz (1970). One difference between the assumptions and procedures employed in the two methods concerned the manner in which the low frequency component of the impulse was assumed to function relative to the human auditory system.

In estimating potential risk of air bag noise Allen et al (1971) suggest that no evidence exists which indicates that the low frequency component is contributing to measured auditory temporary threshold shift (TTS), consequently the pressure wave should be removed from the signal when analyzing the high frequency component. Their estimates of risk are based upon computations which employ this interpretation. Mertz (1970), on the other hand, suggests that "a more realistic evaluation of the pressure wave would require ear tolerance restrictions on both high and low frequency components." The latter procedure proposed for estimating risk includes both components and is described as a general pressure wave analysis system for use with impulsive air bag noises of all types.

The contribution of the low frequency pressure pulse to the effect of the composite signal on the auditory system is of practical significance. If the pressure pulse increases risk, to ignore it underestimates its hazard if the pressure pulse is negligible, to include it overestimates risk, either of which could be costly. The components of the specific air bag stimulus have not been separated and examined in the past, however the effects of static pressure on hearing sensitivity have been reviewed and investigated by Hansen (1955). He reports a reduction of as much as 12 dB in aural sensitivity under positive or negative middle ear pressure for frequencies below 1500 Hz. Although his stimuli were not impulsive the principle involved might hold for transients as well.

The purpose of this investigation was to determine the relative contribution of TTS of each of the two main acoustic components of an air bag inflation impulse, singly and in combination. Volunteer subjects were exposed to (a) a positive pressure pulse, (b) a noise burst (high frequency) and (c) a combination of a and b presented simultaneously. Threshold hearing levels were measured on all subjects prior to and following exposure to each condition to determine the independent and combined effects of the components of the signal on hearing. A differential effect of the low frequency noise would be indicated by TTS values significantly different from those produced in the other exposure conditions.

IMPULSE MEASUREMENT

The measurement and analysis of the impulsive noise in this investigation were accomplished with the special purpose systems described by Sommer (1973). Conventional sound measurement equipment and sound level meters are not appropriate for defining these signals and will provide erroneous results. The very rapid time history and the intense low frequency and infrasound components require special instrumentation response features. The microphone and its associated equipment must be able to respond to the pressure pulse as well as the higher frequency energy associated with the noise burst, therefore the system response should be from 0 Hz (dc) to at least 10 kHz. Use of instrumentation which does not satisfy these general requirements can result in a loss of part of the signal, phase shift and distortion.

SUBJECTS

Ten male university students in their late teens and early twenties served as subjects in this experiment. These volunteers were paid on an hourly basis for this service. All subjects had normal hearing in both ears for the audiometric test frequencies ranging from 125 Hz to 8 kHz (International Standards Organization, 1964). Each subject was examined by a physician and determined to have no respiratory or middle ear infection. This examination also required that the subject be able to equalize middle ear pressure by a Valsalva maneuver which provided evidence of tympanic membrane mobility and also that the eustachian tube was clear of obstruction.

The tympanic membrane consists of three layers of tissue. In the event of rupture or perforation, only two layers regenerate leaving the healed ear less strong at that weakened point. Scar tissue may be indicative of prior rupture or damage, and possibly a drum membrane more vulnerable to intense impulse noise. Subjects with scar tissue on the tympanic membrane were not included in the study because the actual effects of the maximum levels of the experimental stimulus on such ears were not completely known. Two of the twelve subjects examined for the study did not qualify for participation, one because of tympanic membrane scar tissue, the other because of a head cold.

EQUIPMENT .

The equipment used to generate the (a) positive pressure pulse, (b) noise burst and (c) both in combination can be seen in block diagram form in Figure 1. Hearing threshold levels were measured in an audiometric test room with a special purpose clinical audiometer.

(a) *Positive Pressure Pulse:* The positive pressure pulse was generated by the AMRL Dynamic Pressure Chamber (DPC). The DPC is a human test facility for measuring effects of infrasound on man. Basically, it consists of a 6-foot diameter hydraulically operated piston coupled to an enclosed air volume of approximately 55 cubic feet. When the hydraulic actuator is provided an instantaneous positive voltage, the piston moves forward, displacing the enclosed air volume causing a pressurization of the chamber. Volunteers were not exposed

Figure 1. Block Diagram of Stimulus Generating Equipment

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inside the chamber, instead one ear was coupled to the DPC by an ear cup which was attached to a port opening to the chamber in the manner seen in Figure 1. The rise time of the pressure pulse is approximately 50 ms and is governed by the mass of the piston and the compressibility of the enclosed air volume. The pressure fall time of the DPC can be controlled by providing an air leak of selected size so the pressure can return to ambient at a rate corresponding to the air leak. The wave form of the positive pressure pulse is displayed in Figure 2a. In this investigation the positive pressure pulse was presented at a peak sound pressure level of 165 dB re 20 $\mu N/m^2$ with a rise time of 65 ms and a duration (Δ t) of 960 ms.

(b) *Noise Burst:* The noise burst was generated by a pair of loudspeakers (University Driver Type L-35) and was coupled to the earcup in such a way that it was directed toward the ear. The loudspeaker coupling device was smaller but concentric to the access port used to pass the pressure pulse to the subject's ear. The pressure time history trace of the noise burst is presented in Figure 2b. The rms sound pressure level was 153 dB re 20 $\mu N/m^2$ with a rise time and all time of 25 ms each. The duration of the noise burst, including the rise and fall time, was 400 ms. For the noise burst only presentation, the DPC was not activated.

(c) *Positive Pressure Pulse and Noise Burst in Combination:* The composite signal, i.e., the positive pressure pulse plus the noise burst, required both the DPC and the loudspeakers to be activated simultaneously. Figure 2c shows the pressure time history trace for the composite signal.

Energy spectral density (ESD) analyses were performed on the independent and composite signals used as exposures in this investigation and compared to the ESD of an actual air bag inflation noise measured at the ear level of a right front passenger in an automobile. Inspection of Figure 3 reveals that the positive pressure pulse has its peak energy at 0.5 Hz with a high frequency roll off of approximately 8 dB per octave. The energy in the noise burst is concentrated in the region of 300 Hz to 2 kHz, where it is as much as 5 dB to 15 dB greater than in the actual air bag noise shown.

Limitations in performance characteristics of the signal generation systems prevented an exact simulation of an actual air bag measurement. The characteristics of the simulated signals are considered to be equally as effective as the actual impulses in producing TTS and are more than adequate to demonstrate the principle under investigation.

(d) *Hearing Threshold Level Measurement:* Hearing threshold levels were measured with the subject seated in an Industrial Acoustics Company (doublewall IAC) audiometric test booth. The subject's task was to continuously vary, using a subject control switch, the loudness of the test signal between audibility and inaudibility. These auditory responses were measured with Rudmose Clinical Bekésy type audiometer, Tracor model ARJ-6A. Thresholds of hearing were measured for the left ear only at frequencies of 125 Hz, 250 Hz, 500 Hz, 1 kHz, 1.5 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz, 8 kHz, 10 kHz and 12 kHz. The high frequencies (10 kHz and 12 kHz) were calibrated to Tracor high frequency standards. The audiometer was set for 2 pulses per second and an attenuation rate of 5 dB per second. Hearing level responses were automatically plotted on a standard audiometric record form as a function of frequency

POSITIVE PRESSURE PULSE

NOISE BURST

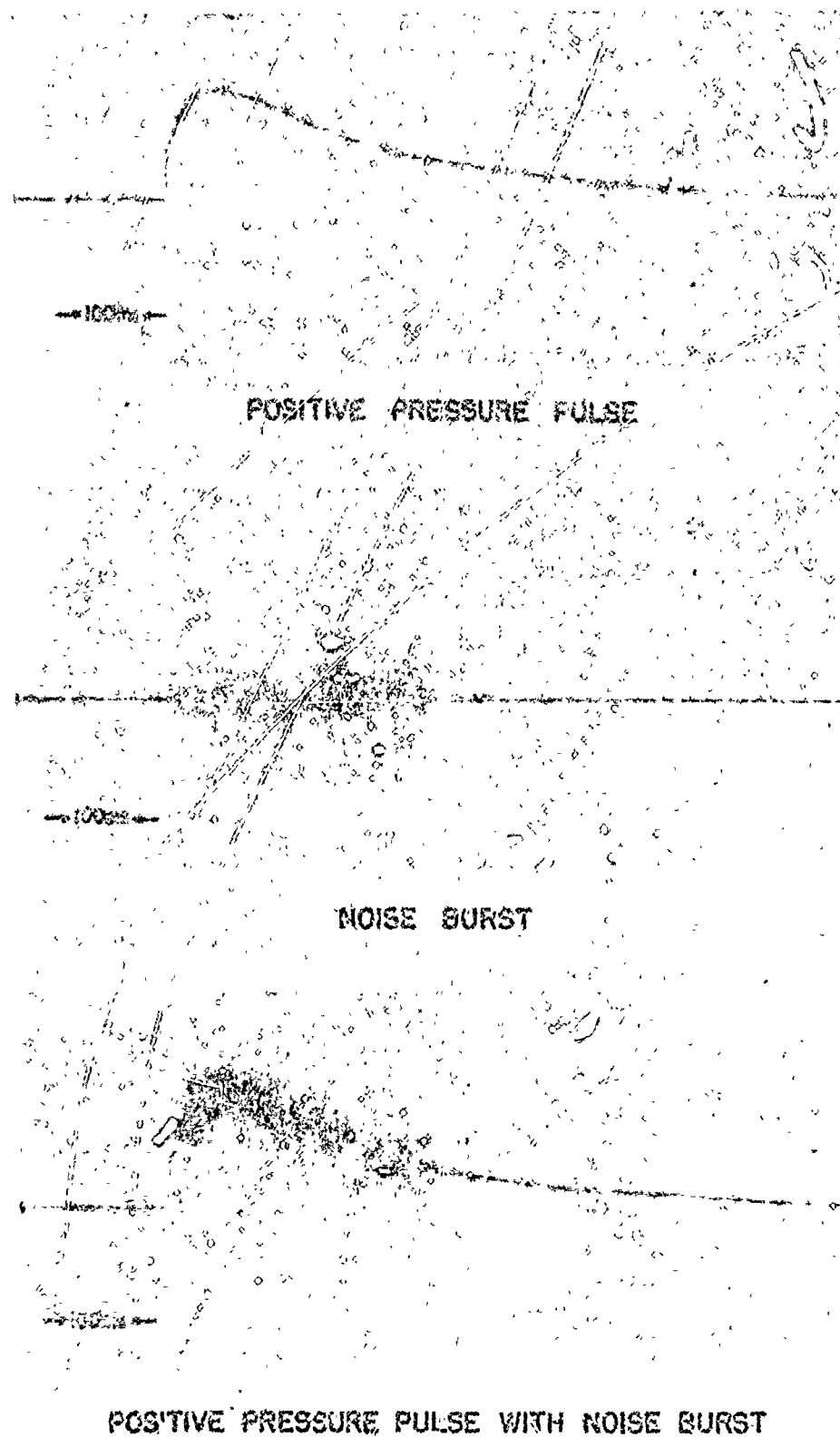POSITIVE PRESSURE PULSE WITH NOISE BURST

Figure 2.   Pressure Time Histories for (a) Positive Pressure Pulse,
(b) Noise Burst and (c) Positive Pressure Pulse With the Noise Burst
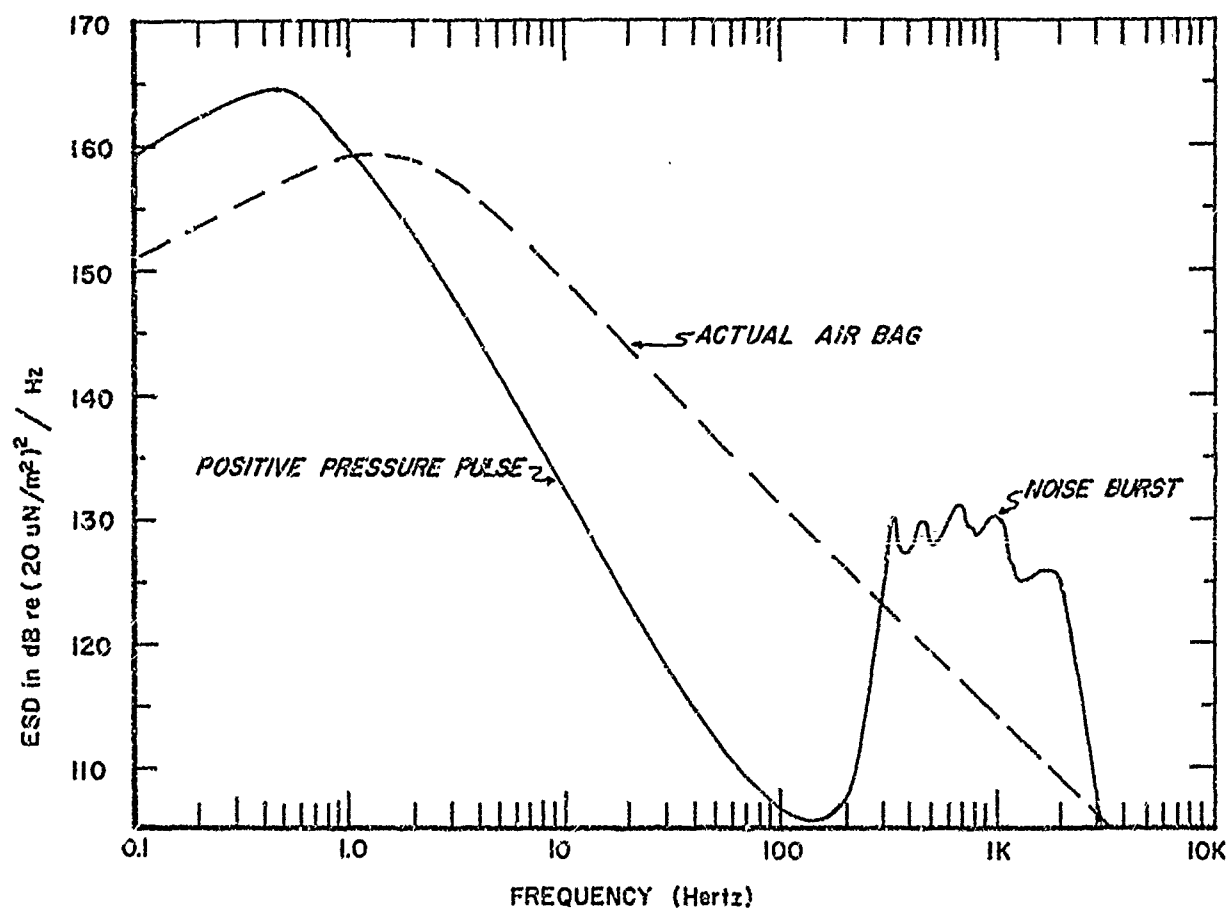
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Figure 3. Energy Density Spectrum of an Actual Air Bag Acoustic Transient
Compared With the Stimuli Used in This Investigation

(see Figure 4). Each audiometric test frequency was presented for 30 seconds and the entire audiogram (12 test frequencies) was completed in 6 minutes.

PROCEDURE

The experiment required subject participation on seven different days. Table I presents the test schedule for each subject. The medical examination, audiometric screening and test instructions were given to each subject on the first day. Subjects also practiced plotting their audiometric thresholds for each frequency on three separate occasions during this initial visit. The experimental procedures followed for the remaining six sessions were exactly the same, only the exposure condition was varied in accordance with Table I. A test session began by giving the subject a brief otoscopic examination of the external auditory canal to insure there was no wax buildup or outer ear infection present. Two preexposure audiograms (125 Hz to 12 kHz), separated by a 5-minute rest period, were then administered. After completion of the second preexposure audiogram the subject moved from the audiometric test booth to the exposure area and placed his left ear in the earcup mounted on the DPC. The subject's left ear was then exposed to the condition specified for that day's session (see Table I). After experiencing the exposure the subject moved from the DPC area and
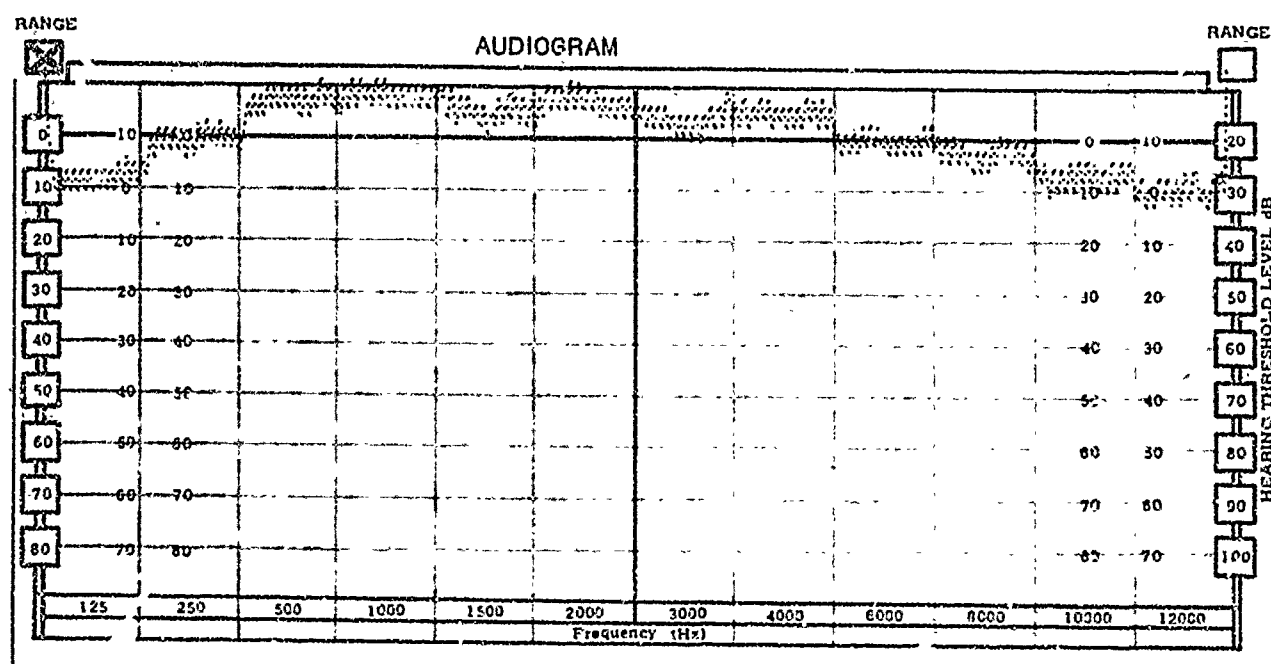

Figure 4. A Typical Audiogram Plot From Which Auditory Sensitivity and Subsequently Auditory Threshold Shift was Determined

TABLE I
TEST SCHEDULE

Subject	Day						
	1	2	3	4	5	6	7
1	Exam	140	145	150	HF	PP	Both
2	Exam	140	145	150	PP	Both	HF
3	Exam	140	145	150	Both	HF	PP
4	Exam	140	145	150	HF	Both	PP
5	Exam	140	145	150	PP	HF	Both
6	Exam	140	145	150	PP	HF	Both
7	Exam	140	145	150	PP	Both	HF
8	Exam	140	145	150	PP	HF	Both
9	Exam	140	145	150	Both	HF	PP
10	Exam	140	145	150	HF	Both	PP

Note 1: Noise intensity levels in dB re 20 $\mu N/m^2$
HF = Noise burst (153 dB_{rms})
PP = Positive pressure pulse (165 dB_{peak})
Both = HF and PP in combination

Note 2: In order to insure that no subject experienced TTS in excess of 30 dB, exposure intensities were gradually increased from 140 dB to 150 dB in successive 5 dB steps. The actual experimental conditions in 5 6-7 were randomized to account for possible order effects.

again entered the audiometric test booth. The subject was asked to perform a valsalva prior to initiation of the postexposure audiometric tests If the acoustic impulse had created a negative middle ear pressure, due to the rapid inward movements of the tympanic membrane, which was not equalized, an erroneous audiogram would have been obtained. The audiogram would have shown TTS due to the exposure plus a threshold shift due to the negative pressure, both of which would have been erroneously attributed to the exposure.

The subject began plotting postexposure threshold of hearing for the exposed ear exactly 1 minute after termination of the exposure stimulus. The temporary threshold shift (TTS) measure for each frequency was obtained by subtracting the average of the two preexposure audiograms from the values of the postexposure audiogram. If a TTS was measured, the subject was periodically tested at various intervals until the TTS had disappeared. All subjects recovered their preexposure hearing levels within 2 hours after exposure.

A criterion for withdrawal from the study was set so that any subject who experienced greater than 30 dB TTS at any test frequency would be eliminated from further participation in the experiment. The procedure used to insure that this 30 dB TTS value was not exceeded, was to increase the intensity of the burst exposures in successive 5 dB steps on days 2, 3 and 4. The exposure schedules were identical for each subject on these days increasing from 140 dB rms to 150 dB rms (dB re 20 $\mu N/m'$) in three steps. If a 30 dB or greater TTS did not occur or was not approached with any of these exposures, the subject was considered not to be unusually susceptible and was allowed to proceed to the experimental conditions for days 5, 6 and 7. The experimental conditions of (1) noise burst (153 dB rms), (2) positive pressure pulse (165 dB peak) and (3) both (1) and (2) in combination were randomized for each subject on these last three days. During the course of their total experiment, no subject experienced sufficient TTS to be dropped from further participation because the 30 dB TTS criterion was exceeded.

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The main effects for test frequency and exposure condition are summarized in Table II. Significant differences between average TTS values were obtained for the main effects of test frequency (p < .01) and exposure condition (p < .05) and also for the interaction of Frequency x Exposure Condition (p < .05).

The mean TTS obtained for each independent audiometric test frequency collapsed over all other conditions is shown in Figure 5. A Newman-Keuls test, used to determine where the significant difference occurred, showed that mean TTS values at 125 Hz, 250 Hz, 500 Hz and 1 kHz were significantly (p < .05) lower than mean TTS values at all other frequencies and that the TTS values were not significantly different within either the 125 Hz thru 1 kHz or the 1.5 kHz through 12 kHz groups. The main effect of the exposure conditions, collapsed over all other conditions, on TTS is presented in Figure 3 in histogram form. The positive pressure pulse produced the least amount of TTS (-0.13 dB). With the noise burst alone having the largest effect (2.99 dB). The combination of the positive pressure pulse with the noise burst produced a TTS greater than that for the pressure pulse alone but smaller than the noise burst alone (1.51 dB). The Newman-Keuls test showed that the noise burst produced significantly greater TTS than the pressure pulse and that the TTS due to the composite signal did not differ significantly from that produced by the noise or pressure pulse alone.

Although there was no statistically significant difference between the effects of the combined noise burst and of the positive pressure pulse or the noise burst alone, the composite signal did produce less TTS than the noise burst. From this observation and reference to Figures 3 and 6, the composite signal does not produce a greater TTS than the noise burst, in fact, the composite tends to reduce the amount of TTS obtained.

The interaction of Test Frequency x Exposure condition can be best understood by referring to Figure 7. The low frequency audiometric frequencies (125 Hz to 1 kHz) were not affected by any of the exposure conditions, however the higher frequencies were clearly differentiated. This difference as a function of frequency and exposure produced the resultant interaction for Test Frequency x Exposure condition Independent analyses for each test frequency showed

TABLE II

SUMMARY ANALYSIS OF VARIANCE

Source of Variance	df	Sum of Squares	Mean Square	F Ratio
1 (Frequency)	11	777.89267	70.71752	4.112**
2 (Exposure)	2	791.62617	395.81303	4.494*
3 (Subjects)	9	959.25344	106.58372	
12	22	705.87117	32.08505	1.764*
13	99	1702.16456	17.10358	
23	18	1740.24103	96.63006	
123	198	3600.23434	18.18300	
Total	359	10277.28400		

*p < .05
**p < .01

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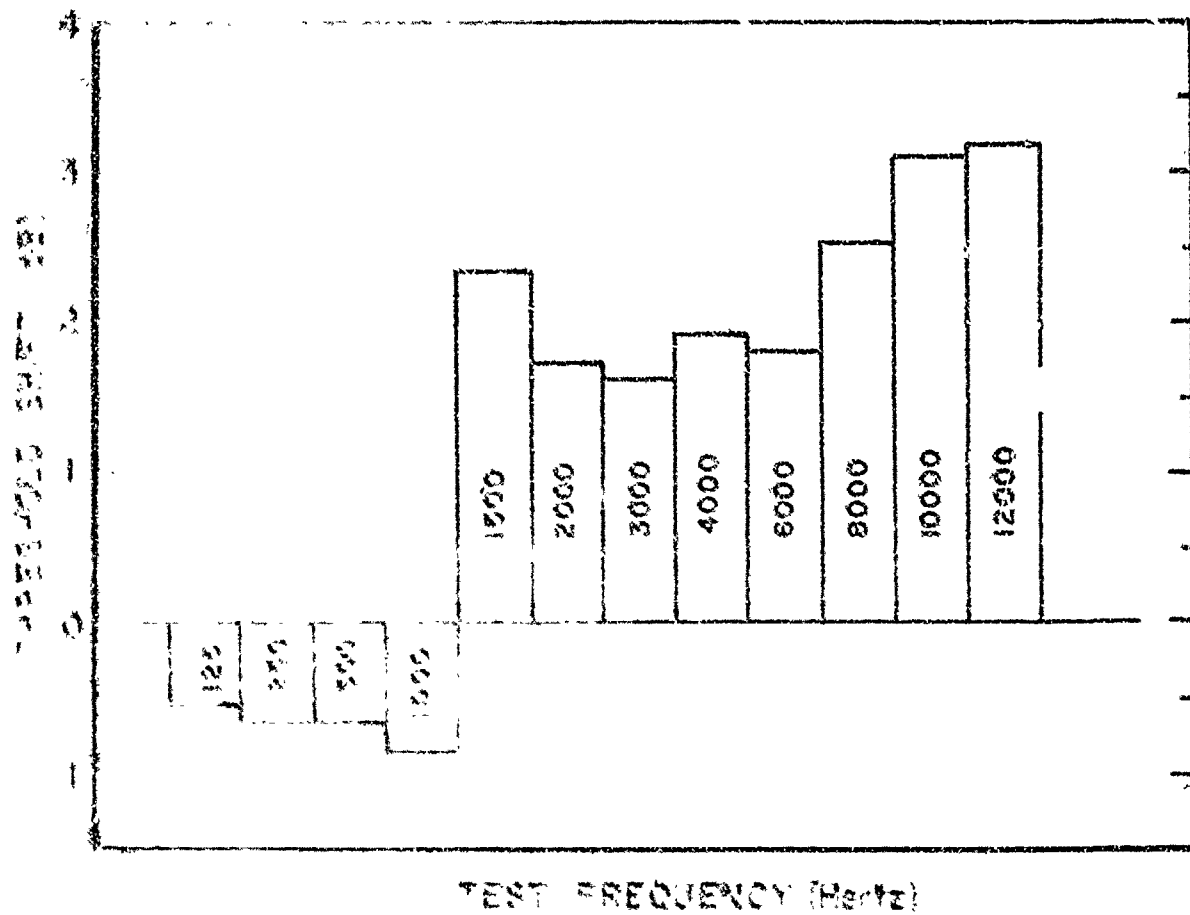TEST FREQUENCY (Hertz)

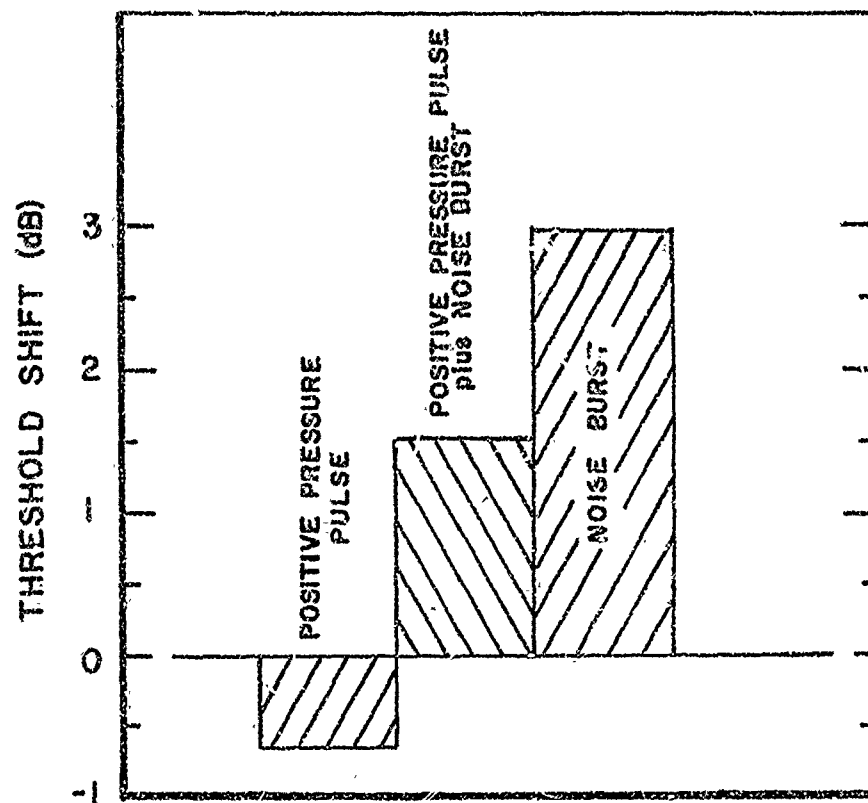Figure 5. Mean Difference in Auditory Threshold Shift as a Function of Test Frequency

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Figure 6.   Main Effect for Auditory Threshold Shift as a Function of Exposure Condition

that the positive pulse produced significantly more TTS ($p < .05$) than the noise burst level at test frequencies of 1.5k, 3k, 4k, 5k, and 12 kHz with the composite exposure significantly different from the noise burst only at 6 kHz.

Prior to dismissal for the day, each subject was informally asked how that day's exposure compared to those experienced on prior days. Nine out of ten subjects indicated that the composite signal (positive pressure pulse plus noise burst) was less objectionable than the noise burst alone, however, all ten subjects reported the positive pressure pulse to be the least objectionable.
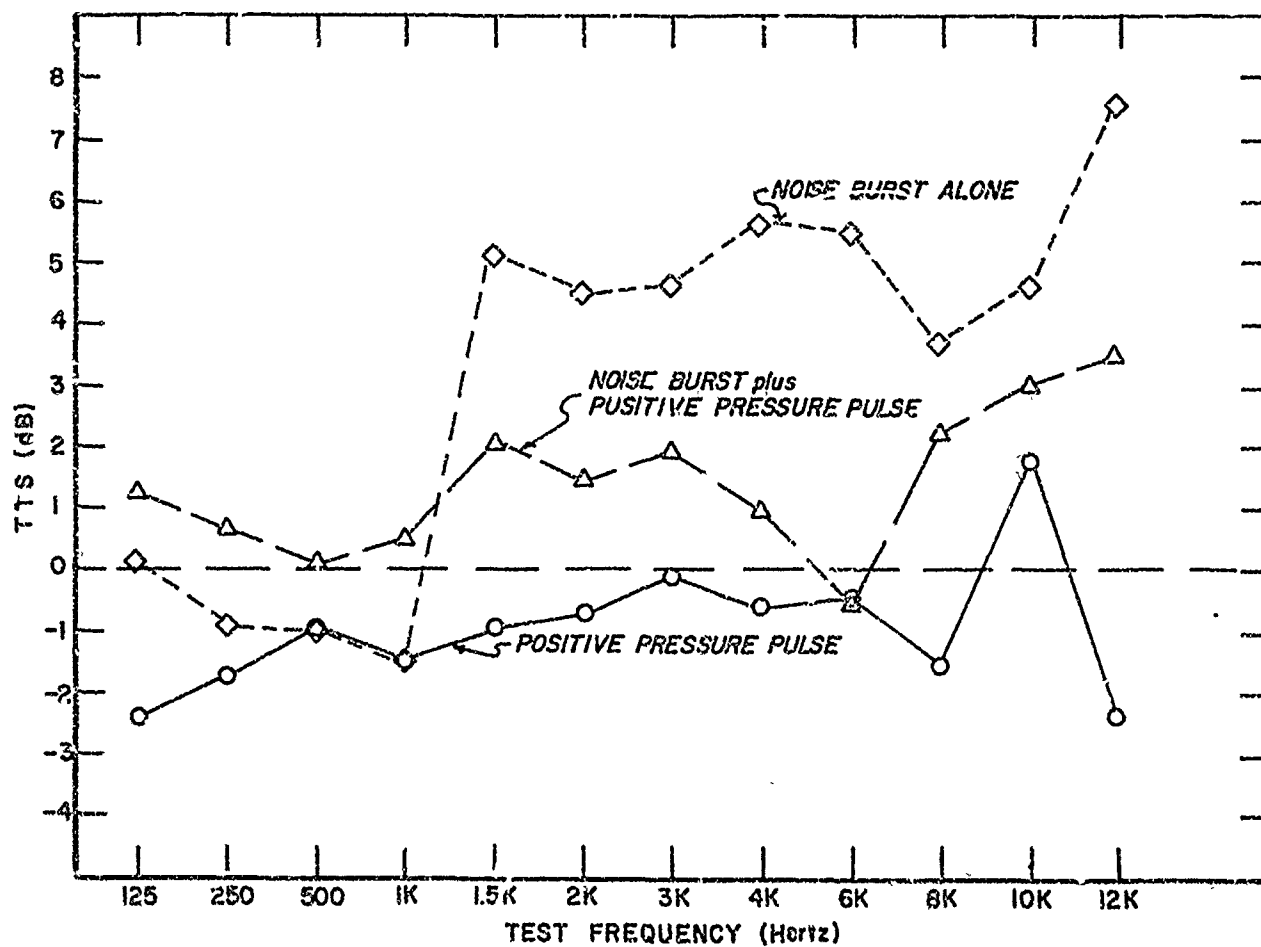
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Figure 7. Auditory Threshold Shift as a Function of Test Frequency and Exposure Condition

SECTION IV
DISCUSSION

The hearing threshold levels of the volunteers in this investigation were differentially shifted (TTS) by each of the three exposure stimuli. The high frequency noise burst clearly produced the greatest TTS at the middle and high test frequencies. The positive pressure pulse caused essentially no changes in hearing threshold levels. The addition of the positive pressure pulse to the high frequency noise burst resulted in lesser TTS values than produced by the noise burst alone. The positive pressure pulse did not add to the effects of the noise burst, but did reduce its effectiveness in causing TTS. A number of interpretations may be offered relative to these findings.

The simulated air bag noise stimulus was selected first to allow the question concerning the positive pressure pulse to be answered and second to somewhat approximate an actual air bag inflation noise in frequency response and level. The simulated signal and an actual air bag noise of equivalent peak pressure level are compared in Figure 3. The energy below 100 Hz in both signals would be expected to produce nearly equivalent TTS on average, if any. The energy above 100 Hz, specifically the 300 Hz to 2 kHz band, is greater in the simulation signal and would be expected to produce relatively more TTS on average. This greater concentration of energy and it's effect on measured TTS does not invalidate any of the findings in this study or their interpretation.

Motor vehicle occupants experience whole body exposures to the air bag inflation noise whereas this study examined effects on only one ear of the subject. To interpret or extrapolate data obtained during this investigation, one must face the question that whole body exposures may produce different effects than exposures only to the ear. Some believe that the opportunity for the middle ear pressure to equalize via the eustachian tube in whole body exposures does not exist for the aural exposure. However, the eustachian tube operates to equalize the atmospheric pressure in the middle ear through actions such as swallowing. The eustachian tube does not normally function during exposure to relatively brief impulsive stimuli, consequently no equalization is expected to occur in either type of impulsive exposure used herein. Therefore, the aural exposure is representative of the response of the auditory system to impulsive sounds such as actual air bag noise can be so interpreted.

The human auditory mechanism reacts in the presence of intense sound with protective actions that reduce transmission to the inner ear. The mode of vibration of the stapes is altered from a piston-like movement to a rocking motion in the oval window due to momentary dislocations of the ossicular joints. In addition, the stapedius and tensor tympani muscles contract in response to loud sound producing an increase in stiffness and possibly in damping of the ossicular chain. The threshold for this muscle action is about 80 to 95 dB above detection threshold of hearing for the various frequencies. The response latency due to neural processing and integration time is nominally from about 25–35 ms up to 100 ms but may be shortened for very intense signals. The reflex reduces transmission of energy of around 2 kHz and below. The acoustic reflex was probably active for all signals used in this study, which ranged from 153 dB to 165 dB with durations of 400 ms and 930 ms and rise times of 25 ms and 65 ms, respectively. The nature of the acoustic reflex is such that its effect on responses measured

in this study is considered to be uniform and not differentiated by the three stimuli, consequently the relationships between them would be unaffected.

The magnitude of the average TTS differences (collapsed over all other conditions) among the three exposure conditions is rather small, 1.5 to 3.0 dB. This may be partly because the sound pressure levels at which exposures occurred were not sufficiently intense to cause large TTS values. Nevertheless, the mean data displayed in Figure 7 indicate clearcut differences in TTS for frequencies above 1 kHz as a function of type of acoustical exposure. Although the sizes of the differences are small, the principle concerning the role of the positive pressure pulse is demonstrated.

The positive pressure pulse produced by an air bag inflation is related to the leak rate of the vehicle in which it is activated. The high frequency energy remains relatively unchanged, except to be riding on the positive pressure pulse or on the ambient in the absence of this component. The positive pressure component would be expected to decrease with increased leak rate. The positive pressure pulse common to a doors closed windows-up configuration would essentially disappear in a convertible with top and windows down. If one were to extrapolate the relative auditory hazard from the closed sedan to convertible situation, the same air bag inflation might well be more hazardous in the convertible, or less hazardous in the sedan, due to the ameliorating effect of the positive pressure pulse on the high frequency energy. Data are not available at this time for air bag inflation noises in open convertibles, however analysis of inflation noises recorded in a large anechoic chamber tend to support this assumption.

The positive pressure pulse is also a function of the air bag volume that displaces the volume of the vehicle interior. Full-car complements of air bag systems could include from three to as many as five inflatable cushions. Since all systems must be inflated within milliseconds after impact, we estimated that the positive pressure produced when all bags are inflated at the same time in an unvented vehicle will be relatively high. This multi-inflation condition is recognized as one area in which additional knowledge and experience are required to be able to assess the impact of the total signal as well as that of the positive pressure component on motor vehicle occupants.

Hearing damage risk criteria for impulsive noises have been formulated for impulses occurring in free field (A-duration) and under reverberant conditions (B-duration) (Coles, 1968). For practical purposes the B-duration has been used to assess air bag impulsive noise because of the reverberation condition inside the vehicle. B-duration analysis of air bag acoustic signature is or may be a reasonable approach for assessing potential hazard to hearing, however, this has not been fully resolved. Air bag noise exposure criteria must give the most consideration to the higher frequency energy.

This investigation considered one aspect of auditory response behavior to an air bag acoustic impulse. It was not designed to explain the mechanisms and interactions involved in the nature of the response. Results were clearcut for the conditions tested and do provide some quantitative indication of the total effects of one positive pressure pulse on one type of high frequency energy, which was the question under consideration. Questions yet to be answered include

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effects of greater and lesser positive pressure pulses on this same noise burst, actual functioning and role of the acoustic reflex, changes in aural impedance of the middle ear system, and the like. A more complete answer to these general questions which involve the mechanisms and interactions should be pursued in subsequent investigative efforts.

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